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Vibration analysis in high speed rough and finish milling hardened steel

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Abstract

High speed milling (HSM) as a cutting process in mould and die industries has been gaining in popularity over recent years due to the ability to machine difficult-to-cut workpiece materials with increased productivity due to an enhanced tool life. A literature survey, however, suggests that work on understanding the chatter vibration effects caused due to various cutter path orientation effects when HSM is scant. This paper presents an approach to derive the vibration analysis on the cutter path orientations employed in rough and finish milling via the use of fast Fourier transform (FFT) analysis on the cutting force signatures obtained based on two cutter condition factors, namely the use of new and worn cutters. The comparative results showed that employing high axial depths of cut ($10\,\text{mm} \leqslant A_d \leqslant 20\,\text{mm}$) for both up and down milling entailed minimal vibrational effects. When finish milling, FFT analysis suggested that employing a vertical upward orientation resulted in minimal vibrations regardless of the cutter condition.

1. Introduction

Chatter is defined as a form of relative structural self excited vibrations between the cutter and workpiece incurred at the cutting zone [1]. Regenerative chatter develops when excessive vibrations provoke larger axial and radial depths of cut than a stability boundary allowed by the structural compliance between the cutter and workpiece [2]. The occurrence of chatter is highly associated with the interaction of the workpiece and flank face wear of the cutter [3] and cutting conditions imposed. This phenomenon is undesirable mainly due to two reasons. Firstly, the

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chatter marks induced on the machined surface affect surface quality and dimensional accuracy. Secondly, it has a detrimental effect not only on tool life but also on the machine tool itself in particular the spindle life. In which case, time and resources will be wasted to introduce additional process to delete the effects.

Direct measurements of vibration are difficult to attain because the characteristic feature of a vibration mode is frequency dependent [4]. Therefore in general, the dynamic force signatures based on a specific cutting condition are extracted from the time domain. Frequency spectrum analysis is then executed to establish more succinct elements such as tool wear and chatter frequency typically characterized by certain frequencies in exceptionally high mode [4,5]. Based on this method, characteristic properties during the cutting process that are clearly not visible in the time domain can be revealed [6]. On the cutting force signatures in the time domain, chatter is categorized with unstable and unperiodic dynamic force signatures superimposed with high peak-to-peak values [7,8]. Ko and Kim [9] performed frequency spectrum analysis and observed that chatter vibration was not evident when employing low depths of cut. Jang et al. [10] on performing spectrum analysis of surface roughness profile on turned surfaces deduced that certain dominant frequencies apart from the tooth passing frequency arose as a result of chip segmentation, deformed workpiece microstructure, etc.

In order to determine the source of chatter or other dominant tool wear frequencies, proper selection of the critical dynamic force signatures is required to perform frequency or power spectrum analysis. El-Wardany et al. [11] on monitoring drill wear, stated that vibration signals were measured in both the transverse and axial directions due to the fact that both directions are influenced by the torque and thrust force which are the major sources of excitation in drilling. Ning et al. [5] stated that normal cutting direction of the dynamic cutting force is the most sensitive to chatter detection due to its lowest damping ratio of the HSM process compared to the other two axes. Dimla and Lister [6] on turning suggested that tangential force components acting on the rake face insert of both cutting forces and vibration signatures were most sensitive to tool wear. Youn and Yang [12] differentiated cutting force components in order to detect the difference between flank and crater wear for varying machining conditions in turning. Their method was used to detect the sudden occurrence of dynamic fluctuations of cutting force in order to indicate the severity of tool life.

Work by Sarhan et al. [13] involving the use of a 4-flute end mill on steel of 90 BHN indicated that the magnitudes of the first harmonics of cutting force frequency spectrum increased significantly with increase in tool flank wear, feed per tooth and axial depth of cut. Therefore, the extraction of the first harmonics from the performance of an FFT analysis can be used as an indicator to detect the variations of the process parameters involved. Elbestawi et al. [14] also had similar observations when face milling AISI 1020 steel and aluminium alloy. As tool wear increases, the dominant and first harmonic peak shift to higher frequencies. Simultaneously, the amplitude of this higher frequency peak increases compared with the amplitude of the dominant lower frequency peak [15]. The deterioration in tool wear increases the tool chip and tool workpiece contact areas and these in turn cause an increase in friction. A worn tool generates high frequency tonal vibrational energy that does not arise in a new tool [16]. Consequently, the noise emitted in the area is amplified [17]. Tonshoff et al. [18] employed the use of acoustic emission signals to determine the influence of a hard turning process on the sub surface microstructure of the workpiece. The results obtained showed that the amplitude of the frequency analysis increased with increasing flank wear due to an enlarged contact area. The comparison of filtered acoustic emission signals without any frequency analysis was used as a function of time to detect and analyze the sub surface damage caused due to thermal and mechanical load induced by the state of the tool flank wear. Lee et al. [19] studied the relationship between the dynamic force and tool wear and reported that the amplitude of the dynamic force of the frequency spectrum analysis increased to a maxima and then decreased as tool wear increased continuously. They asserted that changes in the behaviour of the tool wear patterns and their effects on the tool geometry were the primary causes. Altintas and Chan [2] developed an in-process detection system to detect and suppress chatter by optimizing the spindle speed. It was shown that by oscillating the spindle speed within a short time frame, the magnitudes of the dynamic forces were suppressed, hence the avoidance of chatter.

The parametric study on tool life of a cutting tool during high speed milling (HSM) due to different process parameters has been investigated extensively over the past 20 years. Nevertheless, to understand the conditions of the cutter brought on by the vibration effects due to the cutting process requires a deeper understanding to further aid the analysis. The present study eliminates the use of expensive and complicated equipment set-up to analyze vibrational data, but rather to interpret the vibration analysis via the fast Fourier transform (FFT) analysis on the cutting force signatures obtained. Subsequently, the analysis provided an understanding and aimed to achieve an optimum cutter path orientation during rough and finish milling to attain an enhanced tool life.

2. Experimental work

2.1. Equipment, workpiece materials and tooling

Hardened AISI H13 hot work tool steel with a nominal composition of 0.38% C, 1.00% Si, 0.35% Mn, 5.00% Cr, 1.30% Mo, 1.00% V and Fe balance was used throughout the experimental work. Its hardness was measured with a portable hardness tester to ensure that a nominal bulk hardness of 52 HRC was achieved. A 5-axis electrical discharge wire-cutting machine was used to cut the workpiece materials supplied in block sizes specially prepared to be mounted on the dynamometer platform. Before beginning the machining tests, the blocks were face milled and ground on the top and bottom surfaces to remove any surface defects and to ensure flatness to prevent any bias to the results.

The cutters used in the test were ultra-fine grain tungsten carbide 6-flute corner radius end mills for rough milling and 6-flute ball nose end mills for finish milling. The cutters had a diameter of 10 mm, helix angle of 45° and a radial rake angle of $-14°$. The cutters were coated with a mono-layer (Al,Ti)N film with film thickness of about 2.5 μm. All cutters were checked to ensure a tool runout of less than 10 μm. These were assessed prior to tests using a dial indicator with a resolution of 0.001 mm. Tool wear measurement was based on tool deterioration phenomena observations set out on ISO 8688-2 [20]. Tool wear was measured using a toolmaker's microscope with a magnification of 30× equipped with digital micrometer heads.

All cutting tests were performed on a vertical prismatic high speed machining centre. All cutting force measurements were performed dry. Cutting force measurements were carried out using a three-component piezoelectric platform dynamometer. This has a resonant frequency of 2.3 kHz in the x and y axes and 3.5 kHz in the z-axis. The dynamometer was connected to a series of charge amplifiers type which in turn were connected to a four channel oscilloscope with a maximum sampling rate of 200 M samples/s. The whole system was checked and calibrated prior to use. The cutting force data was downloaded from the oscilloscope and information on cutting force signatures were stored onto a floppy disk and post processing of the cutting force data analysis was performed using software. A FFT program was specially written to carry out vibration analysis.

2.2. Experimental design and procedure

2.2.1. Rough milling

Cutting force measurements at a cutting speed of 314 m/min and feed rate of 4000 mm/min were carried out to determine the effects of up and down milling using new and worn cutters. In this experimental work, the new cutter was interpreted as having a flank wear land width of less than 0.05 mm. Alternatively, the worn cutter was construed as having a flank wear land width equal to or exceeding 0.3 mm. Fig. 1 denotes the cutting force components and its set-up.

Replications were carried out five times to ascertain the results. The cutting conditions were fixed as below; cutting speed of 314 m/min (10000 r.p.m.), feed per tooth of 0.0667 mm/tooth (4000 mm/min), axial depths of cut of 20, 15 and 10 mm and a radial depth of cut of 0.5 mm. These conditions were chosen to characterize high metal removal rates at high cutting speeds. In addition, a tool overhang length of 40 mm was employed throughout the tests.

The cutting force measurements were triggered and recorded as the cutter reached the midpoint of the workpiece so as to achieve complete stabilization and avoid the transient state. Each recorded cutting force signature consisted of three components with 5020 data points per cutting force component. It became evident that the dynamic F_Y force was the most sensitive to changes on the cutting conditions imposed [21] and, therefore, it would be appropriate to transform the dynamic data from the time to frequency domain through implementation of an FFT algorithm to view frequency components classified as chatter [6]. Ning et al. [5] also stated that Y cutting direction of the dynamic cutting force is the most sensitive to chatter detection due to its lowest damping ratio of the HSM process compared to the other two axes.

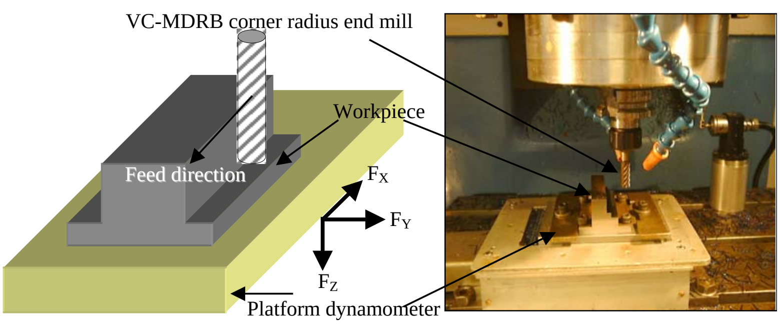

Fig. 1. Cutting force components and measurement set-up for rough milling tests.

2.2.2. Finish milling

Fig. 2 illustrates the cutter path down milling orientations employed in this test on an inclined workpiece angle of 75°. Cutting force measurements on both up and down milling orientations were conducted. Fig. 3 denotes the cutting force components and its set-up. Because of the extreme workpiece inclination angle chosen, a tool overhang length of 60 mm was employed to avoid tool holder collision with the workpiece set-up. An inclined block made of aluminium alloy was specially constructed for this force measurements trial to create an inclined surface. The wired electrical discharge machined workpiece was then mounted on the block. Each trial was carried out five times in order to improve the reliability of the results. When employing a maximum cutting speed of 400 m/min, resonance occurred because the tooth passing frequency exceeded the natural frequency of the dynamometer resulting unreliable data produced. Therefore, a maximum cutting speed of 100 m/min was used instead to avoid the above-mentioned problems. The calculated spindle speeds and feed rates would be 3241 r.p.m., 1945 mm/min and 3295 r.p.m., 1977 mm/min for upward and downward cutting, respectively. The axial and radial depths of cut were fixed as 0.5 mm with a feed per tooth value of 0.1 mm/tooth. The maximum cutting force measurements and vibration analysis carried out were in correspondence with the rough milling force measurement trials.

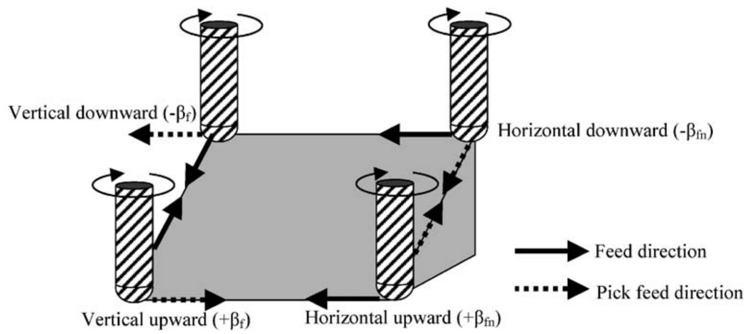

Fig. 2. Cutter path orientations employed in finish down milling an inclined surface of 75°.

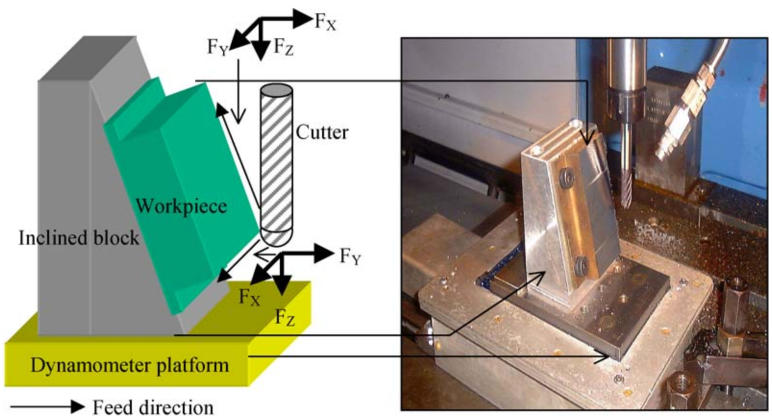

Fig. 3. Cutting force components and measurement set-up for finish milling tests.

3. Results and discussion

3.1. Rough milling

Fig. 4 compares the frequency spectrum of the FFT analysis transformed from the dynamic F_Y force signatures between down and up milling orientation derived from using a new cutter. The dominant peak frequency that occurred at 1000 Hz corresponds to the tooth passing frequency of the cutting tool. This was followed by its harmonics at 2000 and 3000 Hz. The spindle frequency of 166.67 Hz is another known dominant frequency generated during cutting with much lower

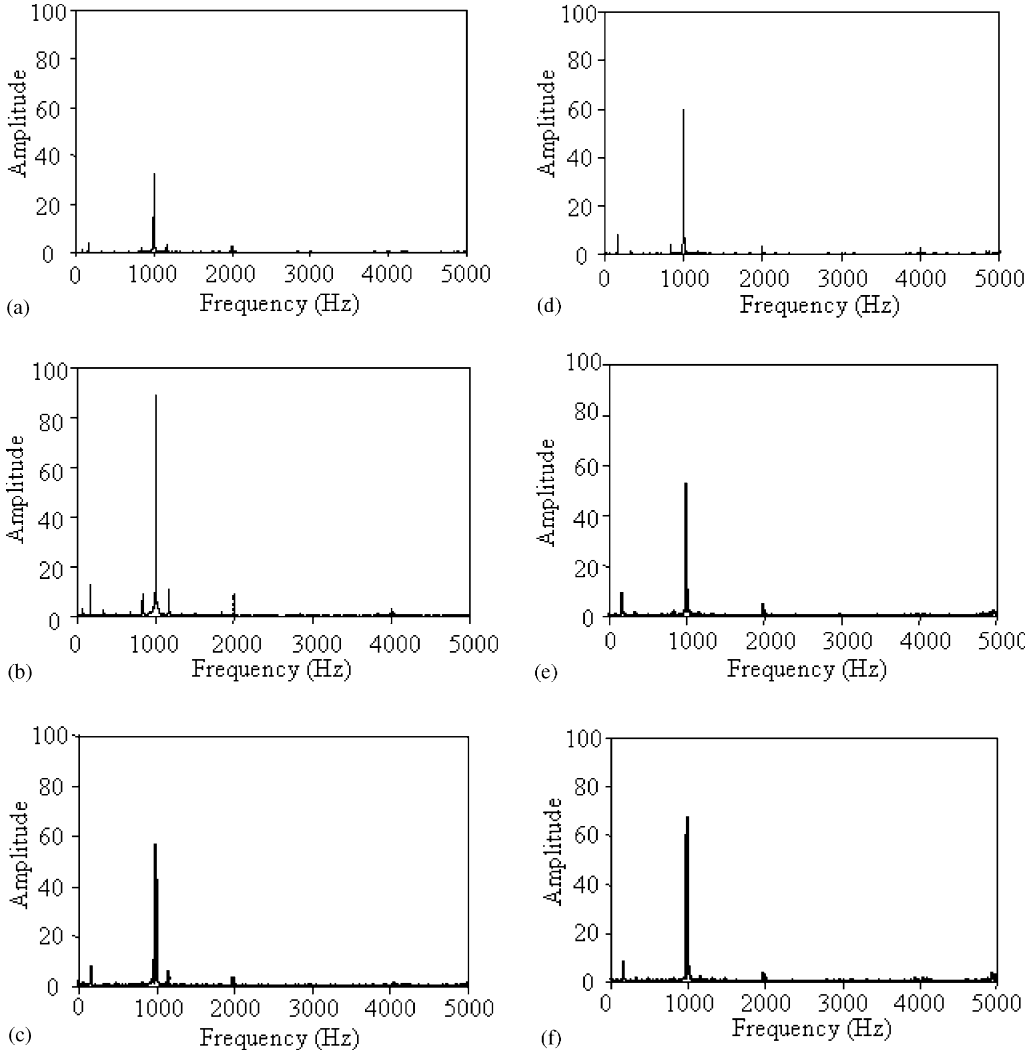

Fig. 4. FFT analysis on F_Y cutting force signatures derived from using a new cutter at 314 m/min cutting speed and 0.5 mm radial depth of cut. (a) A_d = 10 mm, down milling, (b) A_d = 15 mm, down milling, (c) A_d = 20 mm, down milling, (d) A_d = 10 mm, up milling, (e) A_d = 15 mm, up milling and (f) A_d = 20 mm, up milling.

amplitude compared to the tooth passing frequency. Relatively small peaks can be seen manifesting around the tooth passing frequency and is especially evident in Figs. 4(b)–(d). Those peaks could be highly related to cutter runout in the form of radial deflection and the deflection modulation due to chip thickness variation [2].

Apart from that, no other distinct dominant frequencies reminiscent of chatter vibrations were observed in the frequency spectrum regardless of up and down milling orientation. Chatter frequency usually characterized as high mode frequencies typically occurs at a range from 2000 to 5000 Hz when HSM at a spindle speed between 10 000 and 30 000 r.p.m. [5]. In this case, no distinct frequencies were observed at the frequency spectrum between 2000 and 5000 Hz in Fig. 4. This suggests that no distinct chatter vibrations occurred during up or down milling when high depth rough milling using the stated cutting conditions. The amplitude here was directly related to the cutting energy generated to shear the workpiece area of cut from the sharp cutting edge. Comparisons made between the up and down milling orientations indicate that the amplitudes of the dominant tooth passing frequencies when up milling were higher than the down milling orientation at axial depths of cut of 10 and 20 mm. In contrast, the amplitude of the tooth passing frequency when up milling at an axial depth of cut of 15 mm was lower than its counterpart.

Because of the changes brought on as the cutting process continued, the effect of using a worn cutter on dynamic F_Y force was taken into account to realize a more in-depth analysis. The frequency spectrums of the FFT analysis transformed from the dynamic F_Y force signatures are depicted in Fig. 5. It is observed that all the amplitudes of the peak tooth passing frequencies irrespective of the milling orientation when employed with a worn cutter increased as compared to using a new cutter. Such increases are attributed to the additional frictional energy that was dissipated due to the enhancement of the tool flank wear [22], since an increase in tool flank wear increased the cutter workpiece contact area that ultimately led to an increase in friction and as a consequence, an increase in the noise emanated from the contact area. It is reported [3] that when up milling, the cutting force fluctuates and causes transient vibration at the beginning of the engagement between the cutter edge and workpiece. This transient vibration develops into the self-excited primary chatter vibration due to the interference effect between the flank face of the cutter edge and the workpiece as the undeformed chip thickness varies from thin to thick. In contrast when employing a down milling orientation, a transient vibration causes a significant amount of vibration energy due to the large impact when the cutter edge engages the workpiece at the beginning of a cut. Immediately as the undeformed chip thickness goes from thick to thin, the primary chatter vibration of almost stable amplitude continues and dissipates the vibration energy caused by the initial cutter workpiece engagement. Fig. 5 also shows that high frequencies of chatter vibration occurred at the spectrum range from 1000 to 5000 Hz regardless of the cutter conditions. However, all these peaks had little if not insignificant amplitudes that would hinder the tool life of the tests carried out. This effectively means that up milling did not result in excessive vibrations and because of its lower amplitude at all axial depths of cut as compared to down milling, would be effectively translated into better tool life when using a raster (consecutive up and down milling) strategy. In addition, the high hardness and superior oxidation temperature of the (Al,Ti)N coatings coupled with high adhesion to the carbide substrate was able to contain the abrasive and chemical wear caused during cutting [23,24]. Consequently, little or no chipping occurred and that translated into little or no chatter caused during the cutting process.

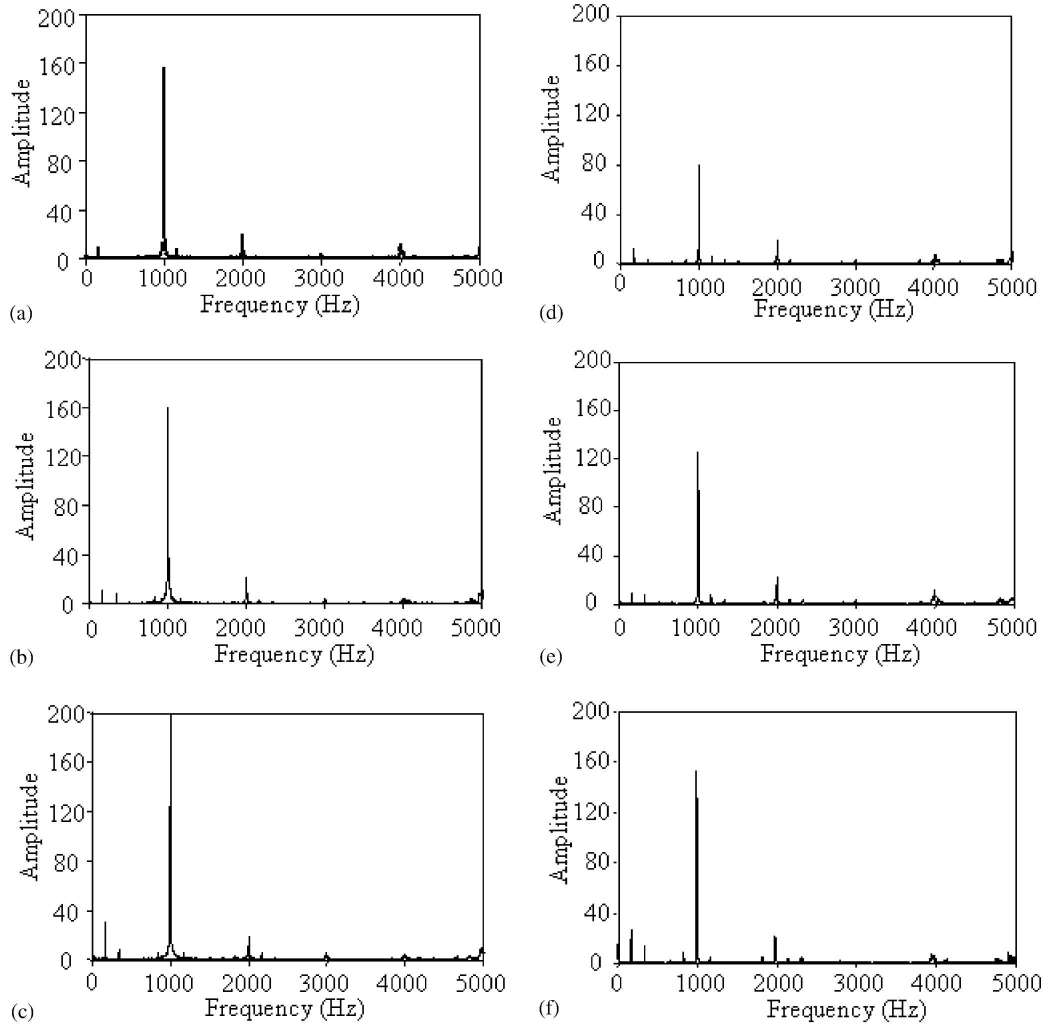

Fig. 5. FFT analysis on F_Y cutting force signatures derived from using a worn cutter at 314 m/min cutting speed and 0.5 mm radial depth of cut. (a) A_d = 10 mm, down milling, (b) A_d = 15 mm, down milling, (c) A_d = 20 mm, down milling, (d) A_d = 10 mm, up milling, (e) A_d = 15 mm, up milling and (f) A_d = 20 mm, up milling.

With reference to Fig. 6, the shoulder workpiece surfaces formed by up and down milling, respectively, had rather straight, constant and slight curvy marks. In contrast, the dominant chatter marks deflected distinctly at an angle formed as a result of the regeneration of waviness on the machined surface [25]. As the cutting edge cut into the workpiece, the relative vibration between the workpiece and cutter increased and as a result, this regenerative vibration caused chatter marks left on the previous revolution as the cutting edge moved to the next revolution. In stable milling, such vibrations are maintained or sustained and therefore revolution after revolution, the surface left constant uniform marks that are evenly spaced out. In this case when down milling at an axial depth of cut of 15 mm, the F_Y cutting force acting against the shoulder workpiece surface was higher when down milling as compared to up milling resulting in

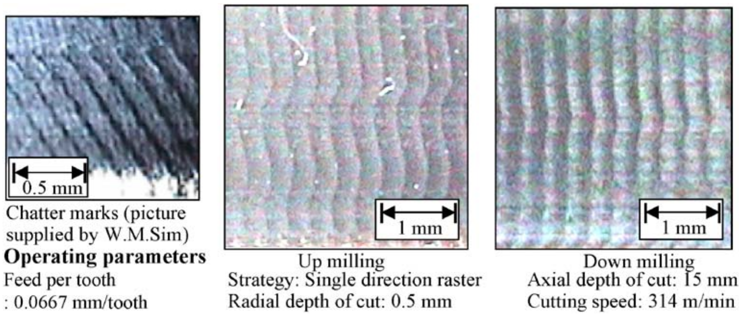

Fig. 6. Comparison of the appearance of the shoulder workpiece surfaces displaying characteristic chatter marks and between up and down milling orientation.

an overcut surface. Therefore, the shoulder surface appearance looks rougher than the surface caused by up milling orientation. In fact, Lee and Ko's results [26] also show that when milling at high axial depths of cut, cutting forces in the F_Y direction were lower in up milling than down milling. As a consequence, up milling produced a more accurate surface with fewer overcuts than the surface produced by down milling.

3.2. Finish milling

Although cutting speed of 100 m/min was used, Hashimoto et al. [3] state that "…the primary chatter development is not influenced quantitatively by changes in arbor rigidity and cutting speed…" The F_Y cutting force components are regarded as the most sensitive to cutter and chatter vibrations because the direct contact between the cutter relief and clearance face with the workpiece surface provides a major source of excitation to detect chatter vibrations. Ning et al. [5] also stated that F_Y cutting direction of the dynamic cutting force is the most sensitive to chatter detection due to its lowest damping ratio of the HSM process compared to the other two axes. Fig. 7 presents the FFT frequency analysis of the F_Y cutting force signature components obtained for down milling with various cutter path orientations when machining with a new cutter. Here, the fundamental dominant peak frequency with the highest amplitude for downward and upward cutter path orientations corresponds to the tooth passing frequency of 324.1 and 329.5 Hz, respectively. The subsequent spectral lines are the harmonics that relate to the tooth passing frequency. The amplitudes of the fundamental tooth passing frequencies when employing upward cutter path orientations were observed to be higher than that of downward cutter path orientations. Apart from that, no significant chatter vibration frequencies were observed in the higher frequency spectrum. This implies that the F_Y forces due to the contact between the flank face of the cutter and the workpiece were higher. This higher F_Y force would increase the tendency towards tool wear deterioration. Furthermore, since no chatter frequencies were observed to occur, this would suggest that tool wear when employing an upward cutter path orientation was a dominant process and chatter vibrations at this stage were unlikely to play a significant role. More significantly for vertical upward cutter path orientation, the harmonics with significant intensities between 1000 and 3000 Hz were highly indicative that cutter deflections possibly due to cutter runout occurred with large magnitudes, which would result in the crumbling of the cutting edges.

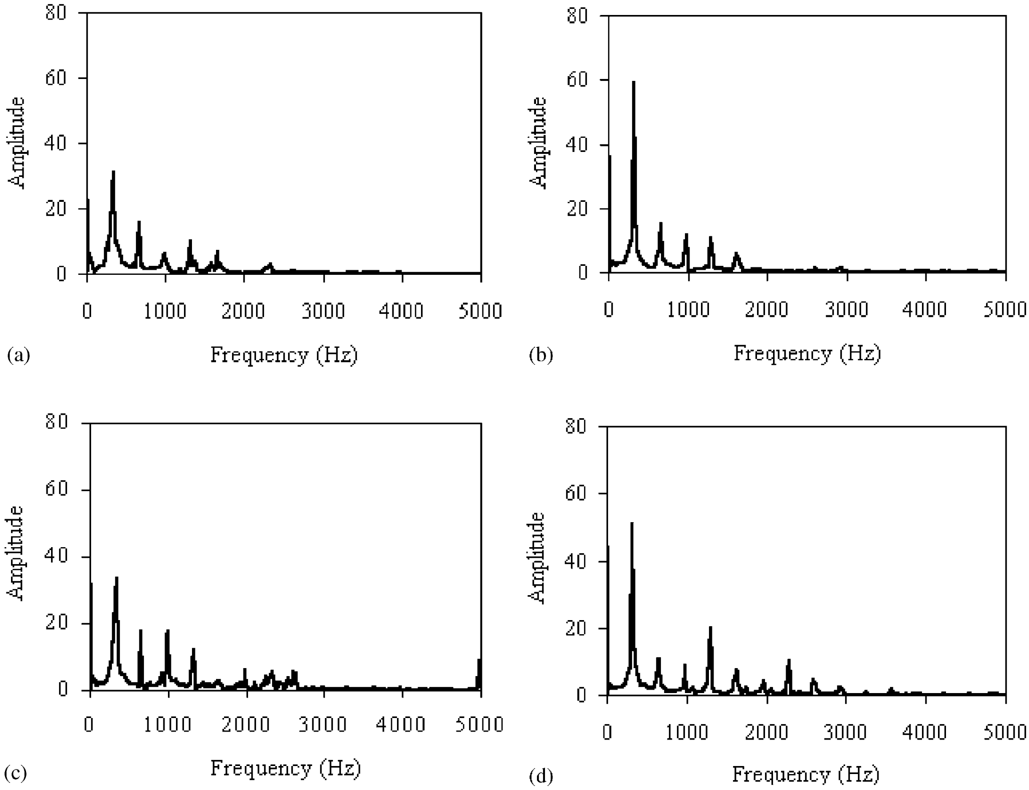

Fig. 7. FFT analysis on F_Y force signatures derived from using a new cutter when down milling and employing various cutter path orientations at 100 m/min cutting speed, 0.5 mm axial and radial depth of cut and 0.1 mm feed per tooth. (a) Horizontal downward ($-\beta_{fn}$), (b) horizontal upward ($+\beta_{fn}$), (c) vertical downward ($-\beta_f$) and (d) vertical upward ($+\beta_f$).

This may be the reason for low tool life obtained when employing a single direction vertical upward and horizontal upward cutter path orientations. On the other hand, the lower amplitudes of the fundamental dominant peak frequencies obtained when employing downward cutter path orientations suggest that the forces induced were lower hence a longer tool life obtained. However, the intensities between 2000 and 3000 Hz were characterized by short oscillatory transients typical of chatter frequencies. In particular, this was more significant for vertical downward orientation. This was most likely due to the bending vibrations of the cutter that constantly hit against the workpiece surface.

Fig. 8 presents the FFT frequency analysis of the F_Y cutting force signature components obtained for up milling with various cutter path orientations when machining with a new cutter. It can be observed that the intensity of the fundamental tooth passing frequency for horizontal downward orientation is slighter lower than its harmonics. In this case when up milling, the cutter ploughed into the workpiece and sheared the chip in a thin to thick fashion. Because the cutting forces tended to push the cutter into the workpiece surface, this would result in a greater than expected area of contact [21] and thus might result in overcut conditions. On the one hand, ploughing action might result in a stable cutting. On the other hand, interference between the

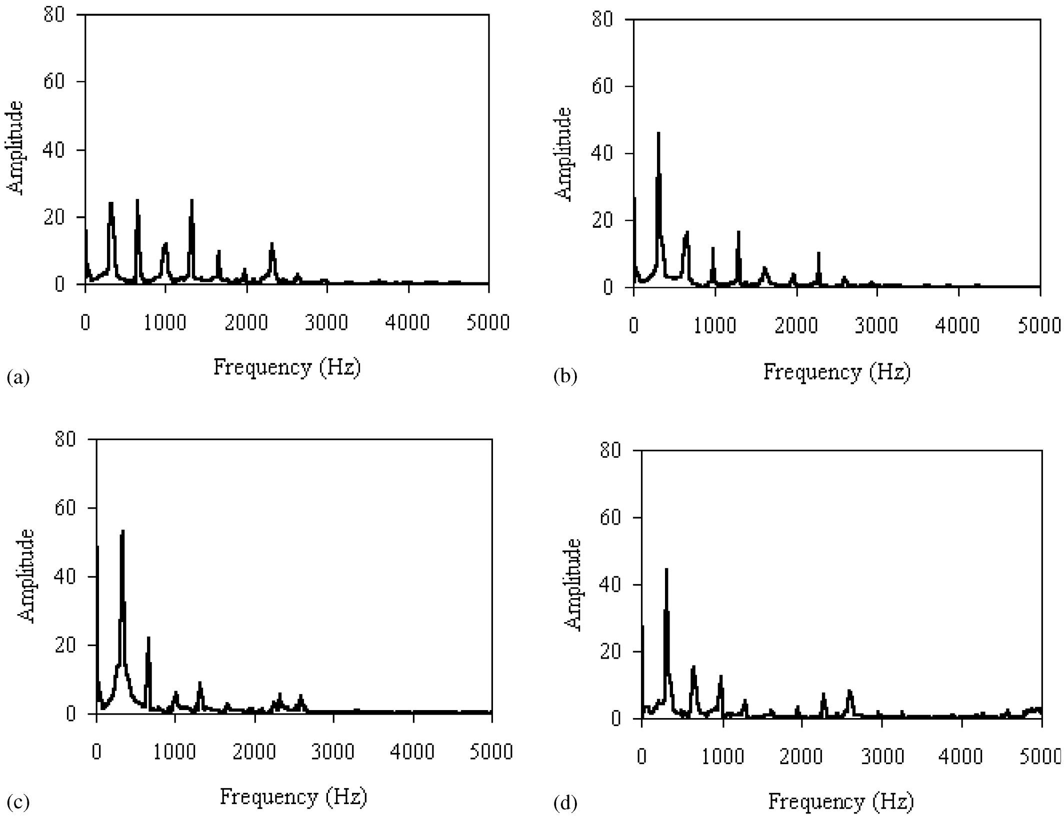

Fig. 8. FFT analysis on F_Y force signatures derived from using a new cutter when up milling and employing various cutter path orientations at 100 m/min cutting speed, 0.5 mm axial and radial depth of cut and 0.1 mm feed per tooth. (a) Horizontal downward ($-\beta_{fn}$), (b) horizontal upward ($+\beta_{fn}$), (c) vertical downward ($-\beta_f$) and (d) vertical upward ($+\beta_f$).

cutting edge and the workpiece surface increased, hence causing chipping on the clearance face of the cutting edge. For vertical downward orientation, high frequency chatter vibrations were observed to occur between the 2000 and 3000 Hz range. This suggests that the beating effects occurred between the cutter and the workpiece might cause chippings on the clearance face of the cutter.

When employing a horizontal upward orientation, no distinct chatter frequency was observed. The intensities of the harmonics between the 2000 and 3000 Hz frequency spectrum windows were rather high in particular when employing a vertical upward orientation. Such intensities could be due to the increase in contact area of the cutter tool wear. High frequency vibration energy was observed to occur at around a frequency spectrum window range between 4500 and 5000 Hz. However, this was unlikely to cause any effect on tool wear due to its low intensities.

Fig. 9 shows the FFT frequency analysis of the F_Y cutting force signature components obtained for down milling with various cutter path orientations when machining with a worn cutter. As tool wear increased, the dominant and harmonic peaks of the tooth passing frequency would shift to higher frequencies coupled with an increase in amplitudes as compared to the lower frequency

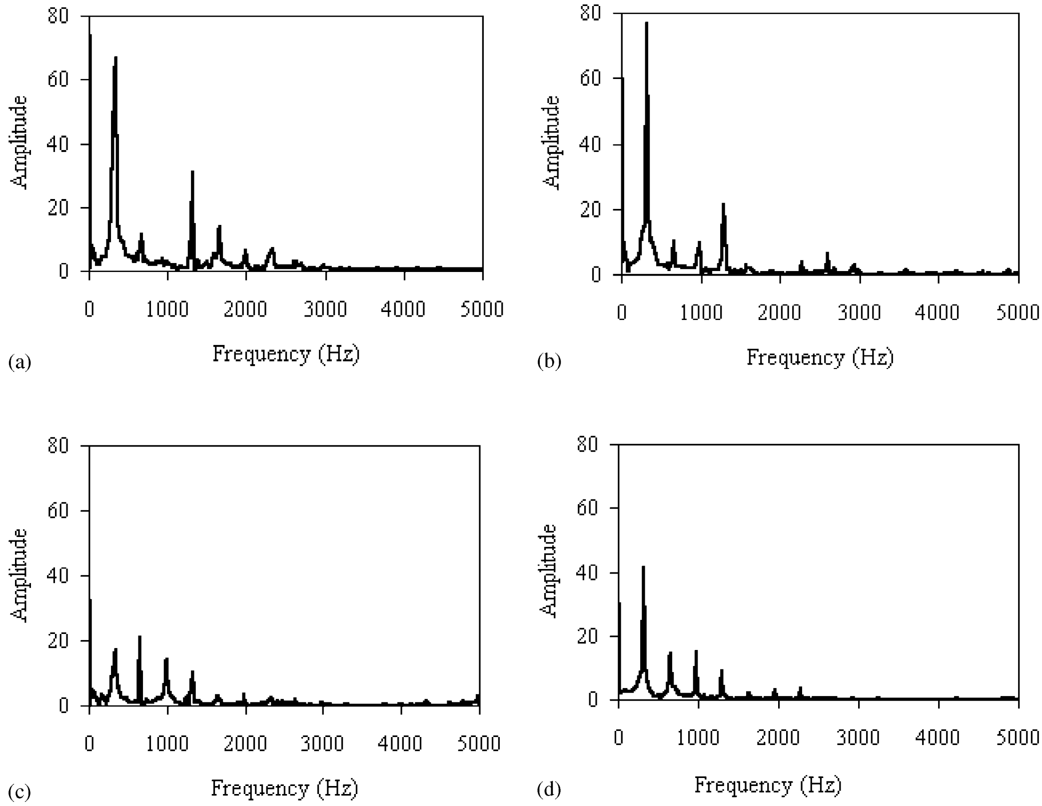

Fig. 9. FFT analysis on F_Y force signatures derived from using a worn cutter when down milling and employing various cutter path orientations at 100 m/min cutting speed, 0.5 mm axial and radial depth of cut and 0.1 mm feed per tooth. (a) Horizontal downward ($-\beta_{fn}$), (b) horizontal upward ($+\beta_{fn}$), (c) vertical downward ($-\beta_f$) and (d) vertical upward ($+\beta_f$).

intensity [15]. When down milling using a worn cutter, the increased flank wear land width induced an increase in frictional forces due to the increased contact between the cutter flank edges and workpiece surface. Furthermore in this case, because of the high tool overhang employed, the tendency towards chipping increased proportionally with the increase in frictional forces. Consequently, one of the teeth might chip more compared to the other teeth. This would definitely result in a larger chip load to be sustained by the following tooth that preceded it, which caused the harmonics at higher frequency spectrum of the tooth passing frequency to increase in amplitude as observed in Figs. 9(a)–(c). Inspection of the cutting edges using a toolmaker's microscope confirmed the phenomenon. As such, varying degrees of vibration energy being manifested was evident between the harmonics and the frequency spectrum window between 2000 and 3000 Hz, see Figs. 9(a) and (b). Although the intensities of the tooth passing frequency and its harmonics were much lower compared to other cutter path orientations, its relatively higher harmonic amplitude and its noise frequency seem to suggest that chatter was rather dominant when employing a vertical downward orientation albeit the fact that crushing of the chips and inability to dissipate it quickly when cutting could be the main cause.

Fig. 10 presents the FFT frequency analysis of the F_Y cutting force signature components obtained for up milling with various cutter path orientations when machining with a worn cutter. Similarly for up milling, the frequency spectrums when employing horizontal downward and horizontal upward orientations display rather high harmonic amplitudes. In particular, the unsettled noise frequencies between the harmonics were more evident when employing horizontal downward, horizontal upward and vertical downward orientations. When up milling, the tendency for the flank cutting edge ploughing into the workpiece increased because the increase in flank wear would result in a subzero clearance angle that would effectively increase the tool chip contact area. Thus frictional or ploughing forces arised and that more or less induced some form of vibration energy. When employing a vertical upward orientation regardless of up or down milling, chatter vibration surprisingly was not evident when compared to that when using a new cutter. The main reason is probably due to the minimal increase in cutting forces induced. In fact, the cutting forces when down milling actually decreased as the cutter wore out. This suggestion is substantiated by the fact that Chiou et al. [27] documented that the contact force is negatively proportional to the vibration velocity. Therefore, the effect of a wear flat resulted in a positive damping on the vibration system. In this case, this is most evident with the fact that the F_Y forces actually decreased as tool flank wear increased. In contrast, the F_X forces increased

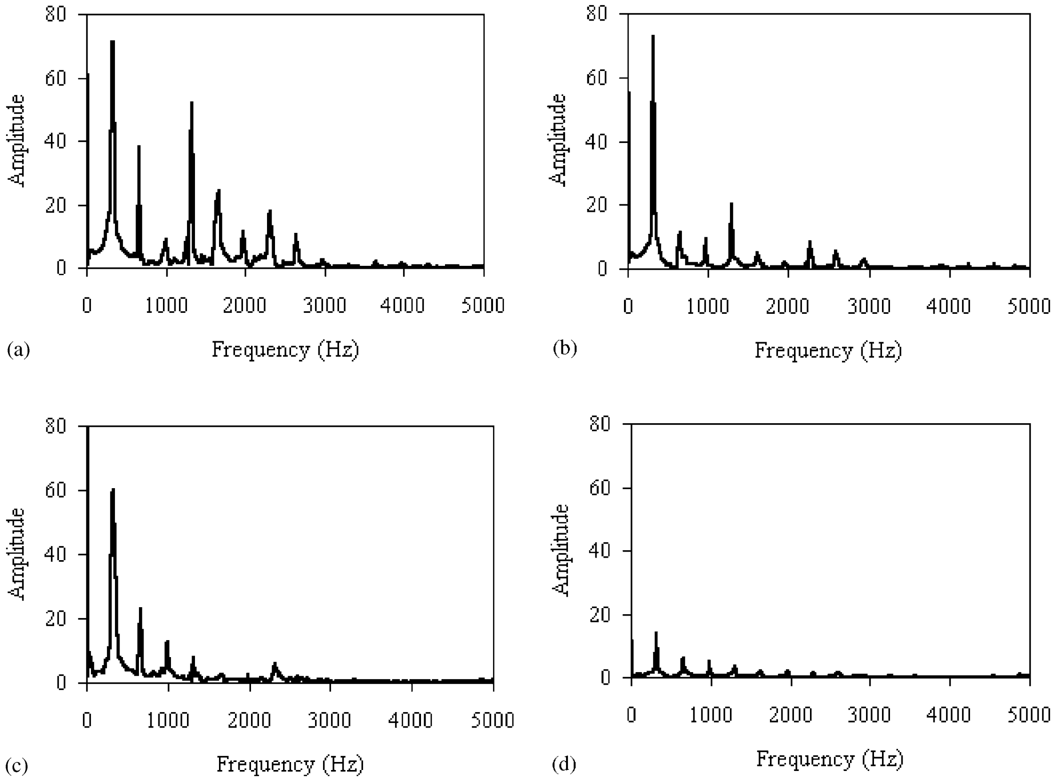

Fig. 10. FFT analysis on F_Y force signatures derived from using a worn cutter when up milling and employing various cutter path orientations at 100 m/min cutting speed, 0.5 mm axial and radial depth of cut and 0.1 mm feed per tooth. (a) Horizontal downward ($-\beta_{fn}$), (b) horizontal upward ($+\beta_{fn}$), (c) vertical downward ($-\beta_f$) and (d) vertical upward ($+\beta_f$).

proportionally resulting in dynamic deflection of the cutter to push towards the workpiece surface rather than outwards or sideways thus creating a so-called damping effect.

4. Conclusions

- For rough milling, comparison of the FFT analysis between the up and down milling orientations at all axial depths of cut employed when using a worn cutter showed that lower magnitudes coupled with little or no vibrations were observed when employing an up milling orientation as compared to a down milling orientation.
- When employing an upward cutter path orientation using a new cutter, the higher amplitudes of the fundamental dominant peak frequencies of the F_Y force increased the tendency for microchipping and macrochipping to occur resulting in a lower tool life. On the other hand, the lower amplitudes of the fundamental dominant peak frequencies obtained when employing downward cutter path orientations suggested that tool wear was progressive hence a longer tool life obtained.
- FFT analysis suggested that chatter vibrations were the most predominant when employing a single direction raster vertical downward cutter path orientation using a worn cutter at a down milling orientation.
- FFT analysis showed that employing a single direction vertical upward orientation, regardless of up or down milling, revealed that chatter vibration was not evident despite using a worn cutter, owing to the fact that the increase in cutting forces were minimal.

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